

(19)



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(11)

EP 0 961 392 A2

(12)

## EUROPEAN PATENT APPLICATION

(43) Date of publication:  
01.12.1999 Bulletin 1999/48

(51) Int. Cl.<sup>6</sup>: H02K 41/03, H02K 5/173,  
H02P 6/00

(21) Application number: 99302535.2

(22) Date of filing: 31.03.1999

(84) Designated Contracting States:  
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU  
MC NL PT SE  
Designated Extension States:  
AL LT LV MK RO SI

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(30) Priority: 08.04.1998 US 58004

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### (54) Method and apparatus for vibration reduction/control in a variable reluctance linear motor

(57) A variable reluctance linear motor has a stator and an armature mounted so as to be movable along the length of the stator. Armature bearings are mounted to the armature via mechanical vibration dampers and contact the stator so that vibrations in the stator are transmitted to the bearings and dissipated in said vibration dampers. A sensor is mounted to the armature for obtaining position data for the armature with respect to the stator. A controller then calculates the phase currents for the motor phases based on the position data

and a desired force value. The phase currents are calculated to maintain a minimum normal force between the armature and said stator, thereby further reducing vibrations. A conditional filter is applied when armature is within a predetermined distance from a desired location. The conditional filter, after a time delay, clamps the velocity feedback to a predetermined range and simultaneously reduces the velocity loop gain.

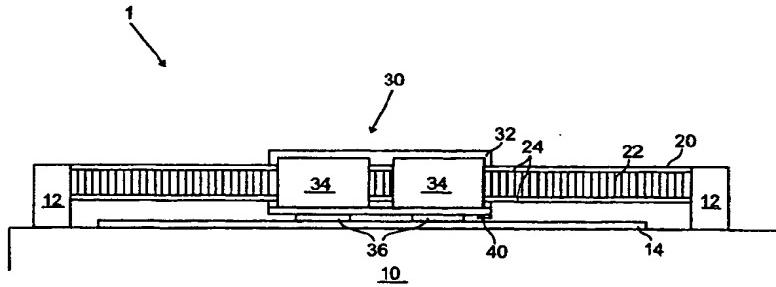


FIG. 1

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**Description****FIELD OF THE INVENTION**

[0001] The present invention relates to a method and apparatus for reducing both the magnitude of, and the sensitivity to vibrations in a variable reluctance linear motor.

**BACKGROUND OF INVENTION**

[0002] In high accuracy servo systems requiring fast settling times and precision positioning any vibrations within the frequency range of the system's required velocity loop bandwidth create a major control system problem with stability. If these conditions are also highly nonlinear or multivariable dependent, the problem becomes even worse.

[0003] In a high accuracy positioning system using a variable reluctance linear motor, these vibration problems occur mainly at the point when the system is moving slowly or approaching the desired location. One cause of these vibrations is the high normal forces associated with the stator and armature of the motor, and the interaction between the stator, armature, bearings, commutation, feedback mechanism, etc., which cause nonlinear vibrations to excite resonance frequencies.

[0004] When such a motor is operating at high accelerations, the currents applied to the motor phases are relatively high. These high currents generate a strong magnetic attraction (normal) force between opposing motor cores. The strong normal force helps to preload the mechanical pieces of the motor and help eliminate any hysteresis or "slop" within the system. As the motor positions the load near its desired location, however, the currents within the motor phases are reduced, thereby reducing the normal force and relaxing the mechanical system. This effective reduction in stiffness adversely affects the velocity loop stability allowing undesirable resonances to occur.

[0005] One way to eliminate or control the vibration would be either to lower the velocity loop bandwidth or increase the friction in the system. These proposed solutions would, however, have negative effects on system performance in the way of settle time, accuracy and temperature rise. Another method would be the use of low order linear filters such as low pass or notch filters. These would have significant effects on velocity loop bandwidth since the vibration/resonance frequency is within the desired system bandwidth.

**SUMMARY OF THE INVENTION**

[0006] It is, therefore, an object of the present invention to provide a variable reluctance linear motor in which vibration is controlled or reduced.

[0007] Another object of the present invention is to

provide a mechanical damper between the stator and armature of a variable reluctance linear motor.

[0008] A further object of the present invention is to provide a variable reluctance linear motor in which the normal force between the stator and armature is kept above a desired level.

[0009] Yet another object of the invention is to provide a variable reluctance linear motor having conditional filtering of the control feedback loop.

[0010] The above and other objects are achieved in accordance with a first aspect of the present invention by a variable reluctance linear motor having a stator and an armature mounted so as to be movable along the length of the stator. Armature bearings are mounted to the armature via mechanical vibration dampers and contact the stator so that vibrations in the stator are transmitted to the bearings and dissipated in the vibration dampers.

[0011] In a second aspect of the present invention, a sensor is mounted to the armature for obtaining position data for the armature with respect to the stator. A controller then calculates the required phase currents for the motor phases based on the position data and a desired force value. The phase currents are calculated to maintain a minimum normal force between the armature and stator.

[0012] In a third aspect of the present invention a conditional filter is applied when the armature is within a predetermined distance from a desired location. The conditional filter, after a time delay, clamps the velocity feedback to a predetermined range and simultaneously reduces the velocity loop gain.

[0013] These and other objects, features and advantages of the present invention will be apparent and fully understood from the following detailed description of the preferred embodiments, taken in connection with the appended drawings.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0014]

Figure 1 is an elevational view of a variable reluctance linear motor according to the present invention.

Figure 2 is a perspective view of an armature module of the linear motor of Figure 1.

Figure 3 is an exploded view of the armature module of Figure 2.

Figure 4 is a schematic diagram of an armature module and the stator of the motor of Figure 1.

Figure 5 is a block diagram of the interface between the controller and armature of the linear motor of Figure 1.

Figure 6A is a graph illustrating the phase current of one phase of a prior art linear motor as a function of motor displacement for fourteen constant force levels.

Figure 6B is a graph illustrating the phase current, according to the present invention, of one phase of a linear motor as a function of motor displacement for fourteen constant force levels.

Figure 7 is a more detailed block diagram of the interface between the controller and armature of the linear motor of Figure 1.

Figure 8A is a graph of the position error and velocity feedback of the system of Figure 7 operated according to the prior art.

Figure 8B is a graph of the position error, velocity feedback and velocity loop gain of the system of Figure 7 operated according to the present invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0015] Referring to Figure 1, a variable reluctance linear motor 1 according to the present invention is illustrated. The motor 1 includes a stator 20 having teeth 22 on both sides. The stator 20 is mounted to a stable base 10 by stator supports 12. An armature assembly 30 is mounted about the stator 20 and supported by linear bearings 36 so as to be moveable along the stator 20. The armature assembly 30 includes two armature modules 34 mounted to an armature carriage 32. A sensor 90 is also mounted to the carriage 32 and interacts with linear encoder 14 to register precisely the location of the armature assembly 30 along the stator 20.

[0016] As illustrated in Figures 2-4, each armature module 34 is an independent coupled three-phase armature. The modules 34 are mounted to the carriage 32 and wired such that the corresponding phases of the two modules 34 act in unison as a single phase. In other words, the modules 34 are mounted to the carriage 32 such that the teeth of the corresponding phases of the armature modules 34 are in identical alignment with the teeth 22 of the stator 20 and identical currents are applied to the corresponding phases. It should be apparent, however, that other arrangements, for example using more modules or only one module, may be employed and still be within the scope of the present invention. Similarly, a different number of phases may be used.

[0017] As best seen in Figures 2 and 3, each armature module 34 is comprised of a top housing 40a and a bottom housing 40b which support the two e-cores 80a and 80b of the armature module 34. In the illustrated embodiment, the top housing 40a and the bottom housing 40b are identical to reduce manufacturing costs. A roller bearing 70 is mounted by shaft 72 and plate 74 to the bottom housing 40b so as to contact the bottom of stator 20. Bearing 70 provides vertical support for the stator 20 as the armature assembly 30 moves along its length.

[0018] The e-cores 80a/b are mounted in the housing 40a/b in opposition such that when in place about the

stator 20, the e-cores 80a/b are positioned adjacent opposite sides of the stator 20 so as to interact with the teeth 22 on both sides. (See Figure 4) The corresponding phases of the e-cores 80a/b are aligned with each other and have identical currents applied to them so as to act as a single phase. The e-cores 80a/b have two shafts 82 at each end (four shafts 82 on each e-core 80a/b) on which are mounted roller bearings 60. The roller bearings 60 travel along the side surfaces of the stator 20 along bearing surface 24 (see Figure 1) above and below the teeth 22 so as to maintain the e-cores 80a/b a constant distance from the stator 20. This arrangement allows the armature 30 to track the stator 20 at a very close distance, 2-3/1000 of an inch in the illustrated embodiment. (See Figure 4).

[0019] The e-cores 80a/b of the preferred embodiment are retained within the housing 40a/b by bolts 62. Although only two of these bolts 62 are shown in Figure 3, it should be understood that four bolts 62 are used for each e-core 80a/b (see Figure 2). The shafts 82 fit into holes 42 in the housing 40a/b. The holes 42 in the housing 40a/b are a transitional clearance fit with the shafts 82 to prevent movement of the shafts 82 in the holes 42. The bolts 62 pass through washers 64 and are threaded into shafts 82. The holes 42 in the housing 40a/b are located at the ends of cantilevered springs 46, which are machined out of the housing 40a/b. The springs 46 provide a suspension that allows the armatures 80a/b to comply to the stator surface and compensates for slight bending or misalignment of the stator 20 as the armature 30 travels back and forth along its length. It should be understood, however, that other biasing element arrangements may be utilized.

[0020] Referring to Figure 2, felt wipers (not shown) may be attached to the ends 46 of the housing 40a/b. These wipers serve the function of applying a light coat of oil on the stator bearing surface 24 to prevent oxidation. In addition, the wipers prevent dust and debris from getting between the bearings 60 and stator 20.

#### Mechanical Damper

[0021] Since the stator 20 is a pseudo simply supported beam, it is highly susceptible to mechanical vibration. In a first aspect of the current invention, this vibration is minimized using a translating damper which is used to damp the stator 20 at the source of the excitation, i.e., the armature 30. In the illustrated embodiment, rigid straps 50 are rigidly mounted to one of the e-cores 80a of each module 34 and attached to the motor housing 40a/b through polymer damping grommets 56. Energy from the stator 20 is thus transferred through the armature bearings 60 into the rigid straps 50 and is dissipated into the damping grommets 56. This reduces the magnitude of the vibration making the system more stable.

[0022] In each module 34 of the illustrated embodiment, four rigid straps 50 are mounted to the e-core

80a. Each shaft 82 of the e-core 80 (on which a bearing 60 is mounted) is fitted within a hole 52 in one of the straps 50. The fit between the shaft 82 and the hole 52 is snug so that vibrations in the stator 20 are transmitted through the bearing 60 to the strap 50. Polymer damping grommets 56 are disposed in mounting holes 54 at either end of the strap 50. Although only two grommets 56 are shown in Figure 3, it should be understood that two grommets 56 are used on each strap 50, for a total of eight for the module 34 shown in Figure 3. The ends of the straps 50 are then mounted to the housing 40a/b by bolts 58 which extend through washers 59 and the grommets 56 and are secured to the housing 40a/b at holes 44. To reduce wear of the grommets 56, metal sleeves 57 are inserted in each grommet 56 to act as a barrier between the bolt 58 and the grommet 56.

**[0023]** As seen in Figure 3, U-shaped apertures 53 are located in the strap 50 to provide clearance for the shafts 82 of the other e-core 80b. These U-shaped apertures 53 are larger than the outer diameter of the shafts 82 to avoid interfering with the movement of the other e-core 80b. This is necessary to allow the armature suspension to comply to the stator 20 keeping the armature bearings 60 in contact.

**[0024]** It should be understood that other alternative arrangements are contemplated and should be considered to be within the scope of the present invention. For example, the bearings 60 which contact the stator 20 need not be mounted to the e-cores 80a/b, but instead may be mounted directly to the armature housing 40a/b via mechanical dampers such as polymer grommets. In such a case, the e-cores 80a/b may be rigidly mounted to the housing (without straps 50) or mounted as disclosed above. In addition, mechanical dampers other than those disclosed may be employed, for example, dampers using pneumatic or hydraulic pressure.

#### Electromagnetic Preload

**[0025]** In accordance with another aspect of the invention an electromagnetic preload in the motor's phase commutation system is employed to further reduce vibrations.

**[0026]** Referring to Figures 4 and 5, in a typical servo motor control, commutation is applied which excites the phases of the motor causing the motor to generate a force in the linear direction of movement. In a closed loop servo driven positioning system the desired force is the result of a closed loop design which derives an output based on the position/velocity errors in the system. Using these values, the system calculates the current required to be applied to each phase in order to achieve the required linear force.

**[0027]** To account for nonlinearities in the system, the currents in the phases are controlled, for example, in accordance with U.S. Patent No. 5,621,294, which is incorporated herein by reference. In accordance with the '294 patent, the sensor 90 mounted to the armature

5 (see Figure 1 herein) determines the position of the armature 30 with respect to the stator 20 and sends that information to a commutation controller 100 and a motion controller 120. The motion controller 120 generates velocity commands in response to this feedback and sends the velocity commands to the commutation controller 100. The commutation controller 100 uses this information, together with the position feedback data to calculate a desired lateral force and to determine the required phase currents to achieve this force using a look-up table and interpolation. The phase currents are then sent to an amplifier 110 which sends the appropriate currents to the armature 30.

**[0028]** Figure 6A illustrates the current in one phase (phase B) as a function of motor displacement from the phase B alignment position for fourteen constant force levels. The currents are periodic for every 12 mm of displacement since the pitch of the teeth 22 on the stator 20 is 6 mm, and current polarity changes every tooth pitch. (See Figure 4). The current waveforms for phases A and C are derived by shifting the graph for phase B (Figure 6A) 8 mm and 4 mm, respectively. Although only fourteen discreet force levels are illustrated in Figure 6A, 64 force levels for 375 individual motor positions were used for the illustrated embodiment.

**[0029]** When the armature 30 approaches the desired location the desired linear force (i.e., force in the direction of movement) approaches zero. Consequently, as can been seen in Figure 6A, the motor control currents also approach zero until the target location is reached. When the target location is reached, the desired linear force is zero, labeled "Zero Force" in Figure 6A, and all phase currents equal zero. This causes a simultaneous reduction in the normal force of attraction between the e-cores 80a/b of the armature and the stator 20 to zero resulting in a reduction in stiffness of the system.

**[0030]** It is the design of one aspect of this invention to embed dynamic offsets into the commutation system which guarantee that the motor phases always have some level of excitation current regardless of desired linear force. These embedded currents sustain the normal force of attraction between the stator 20 and armature 30 of the motor, which keeps the stiffness at a desired level. Figure 6B illustrates the modified current in phase B as a function of motor displacement according to an embodiment of the present invention. The phase currents were selected so as to sustain some normal force without significantly affecting the lateral force produced by the motor. In other words, any change in the lateral force produced by the offset current in one phase is counteracted by offset currents in the other two phases so that the desired lateral force is maintained. Thus, even for the "Zero Force" level, there will be some current in the phase to maintain the normal force between the armature 30 and stator 20. At the same time, one or both of the other two phases will also have some current flowing which adds to the normal force, while counteracting any lateral force produced in

phase B, thereby producing a net normal force with no lateral force element.

[0031] Using the values illustrated in Figure 6B, the motor of illustrated embodiment maintains a normal force of attraction of about 80 lbs. for Zero Force level, which value does not change for the first eight force levels. This value then increases for higher force levels. The added stiffness which results reduces the magnitude of the motors vibrations making the systems more stable.

[0032] It should be apparent to one of skill in the art that the linear motor need not employ the '294 patent to implement the electromagnetic preload of the present invention. Provided some current level is maintained in at least one phase at all times, a normal force will be sustained. The currents used to satisfy the above requirements may be found experimentally using force transducers and DC power supplies for motor phase current control or theoretically.

#### Conditional Filtering

[0033] In a third aspect of the present invention, conditional filtering of the control feedback loop is used to reduce vibrations even further.

[0034] Referring to Figure 7, a more detailed block diagram of the interface between the controller and armature of the linear motor of Figure 1 is shown. As illustrated, the commutation controller 100 includes a differentiating block 104 for differentiating a position value ( $x$ ) read by sensor 90 over time ( $t$ ) to obtain a velocity value ( $dx/dt$ ). The velocity value ( $dx/dt$ ) is sent through a velocity filter 102 to a summing block 103, which compares it with the velocity command from the motion controller 120. The result is sent to a velocity error control block 101, which applies a velocity loop gain and outputs an actual force command. The commutation block 105 receives the actual force command from velocity error control block 101, the velocity value ( $dx/dt$ ) from differentiating block 104 and the position value ( $x$ ) from sensor 90 to calculate the current ( $I_A$ ,  $I_B$ ,  $I_C$ ) required for each phase of the motor. These values are sent to amplifiers 110, which in turn send the corresponding amplified currents to the motor phases.

[0035] As shown in Figure 8A, when operated according to the prior art, the system of Figure 7 is subject to oscillations once the desired motor location has been reached. This is caused, in part, by the high velocity loop gain employed to achieve high-speed operation of the motor. The conditional filtering of the present invention (Figure 8B) alleviates this problem by operating at full velocity loop gain until the position error (actual motor location - desired location) becomes less than a certain specified value. When the position error, as reported by the PID control system 122 of the motion controller 120, is less than the specified value (at time  $T_f$ ) the conditional filter 106 is applied. The position error value at which the filter is engaged is selected empiri-

cally to be larger than the largest disturbance expected to be experienced by the system once the desired location is reached.

[0036] The first stage of the filter 106 is to apply a time delay so the system may complete the normal trajectory and settle to the desired location without a reduction in band width. This is allowable since the mechanical system requires a period of time to unwind (reduce stiffness as the high-normal forces reduce due to lower acceleration requirements and associated lower phase currents). The duration of the time delay is selected to be slightly larger than the time the armature 30 would normally (i.e., without the conditional filter applied) take to travel from the position where the filter is engaged to a steady state at the desired location (before the oscillations discussed above begin). When the time delay has expired (at time  $T_d$ ) the velocity loop gain applied by velocity error control block 101 is reduced since the bandwidth requirements are less to maintain the desired location once it has been reached. The reduction in gain limits the force command and lowers the close loop sensitivity to the unstable vibration elements.

[0037] Another feature of the filter 106 is the simultaneous introduction of a velocity clamp at velocity filter 102, which limits the velocity data fed to the summing block 103 to a predetermined range (see Figure 8B). This component takes advantage of the fact that the system is basically at rest and that only small displacements at low velocities need to be accounted for to hold position. Any small displacement vibrations (i.e., the non-linear vibrations in question) will exhibit a high velocity element due to their vibration frequency. This velocity element will be greater than any expected linear disturbances while holding position. A velocity clamp will limit the velocity feedback to the maximum expected disturbance elements. The velocity clamp thus reduces the systems sensitivity to vibrations by applying a clamp to their value. It should be realized that any small position disturbances with low velocity content will not be affected by the clamp magnitude of the filter allowing the system to respond normally to maintain position.

[0038] If the position error is greater than the conditional filter specified value (either due to change in desired location or large disturbance) the conditional filter is removed and initialized to await again for position error less than the specified value. This filtering causes the system to become less sensitive to a reduction in mechanical stiffness but does not negatively impact the settle time required to come into position, as seen in Figure 8B.

[0039] The present invention has been described in terms of illustrated embodiments thereof. Other embodiments, features and variations within the scope of the appended claims will, given the benefit of this disclosure, occur to those having ordinary skill in the art.

**Claims**

1. A linear motor comprising:  
a stator;  
an armature mounted proximate said stator,  
said armature being movable along the length  
of the stator; and  
at least one bearing mounted to said armature,  
said bearing being in contact with said stator,  
wherein vibrations in said stator are transmitted  
to said bearing and dissipated in at least one  
vibration damper disposed between said arma-  
ture and said bearing.  
5
2. The linear motor of claim 1 wherein said vibration  
damper is a polymer grommet.
3. The linear motor of claim 1 further comprising a stator  
support bearing mounted to said armature and  
contacting a bottom surface of said stator.  
20
4. The linear motor of claim 1 wherein said armature  
comprises:  
an armature housing; and  
at least one core disposed within said housing;  
wherein said at least one bearing is mounted to  
said core and said core is connected to said  
housing by said at least one vibration damper.  
25
5. The linear motor of claim 4 wherein said core is  
retained in said housing by a biasing element.
6. The linear motor of claim 1 wherein said armature  
has at least two phases, said linear motor further  
comprising:  
a controller for calculating phase currents  
based on position data for said armature and  
applying said phase currents to said at least  
two phases;  
wherein said phase currents are calculated to  
maintain a minimum normal force between said  
armature and said stator.  
30
7. The linear motor of claim 6 further comprising  
means for reducing said phase currents when  
said armature is within a predetermined distance of a  
desired location.  
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8. The linear motor of claim 1 wherein said armature  
has at least two phases, said linear motor further  
comprising:  
a controller for calculating phase currents  
based on position data for said armature and  
applying said phase currents to said at least  
two phases;  
50
9. A linear motor comprising:  
a stator;  
an armature mounted proximate said stator,  
said armature being movable along the length  
of the stator;  
means for transmitting vibrations in said stator  
to said armature; and  
means for dissipating said vibrations at said  
armature.  
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10. The linear motor of claim 9 wherein said vibration  
transmission means comprises at least one bearing  
mounted to said armature and contacting said stator.
11. The linear motor of claim 9 wherein said vibration  
dissipation means comprises at least one polymer  
grommet.
12. The linear motor of claim 9 wherein said armature  
has at least two phases, said linear motor further  
comprising:  
means for calculating phase currents for said at  
least two phases based on position data for  
said armature;  
wherein said phase currents are calculated to  
maintain a minimum normal force between said  
armature and said stator.  
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13. The linear motor of claim 12 further comprising  
means for reducing said phase currents when said  
armature is within a predetermined distance of a  
desired location.  
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14. The linear motor of claim 9 further comprising:  
means for calculating phase currents based on  
position data for said armature;  
means for reducing said phase currents when  
said armature is within a predetermined dis-  
tance of a desired location.
15. A method for reducing vibrations in a linear motor  
having a stator and an armature mounted prox-  
mate said stator, said armature being movable  
along the length of the stator, said method compris-  
ing:  
transmitting said vibrations from said stator to  
said armature; and  
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- dissipating said vibrations in said armature.
16. The method for reducing vibrations in a linear motor of claim 15 wherein the step of transmitting said vibrations comprises mounting at least one bearing between said armature and said stator. 5
17. The method for reducing vibrations in a linear motor of claim 16 wherein the step of dissipating said vibrations comprises mounting said at least one bearing to said armature via a vibration damper. 10
18. A variable reluctance linear motor comprising:  
 a stator; 15  
 an armature mounted proximate said stator, said armature having at least two phases and being movable along the length of the stator; and  
 a controller for calculating phase currents based on position data for said armature and applying said phase currents to said at least two phases; 20  
 wherein said phase currents are calculated to maintain a minimum normal force between said armature and said stator. 25
19. The variable reluctance linear motor of claim 18 further comprising means for reducing said phase currents when said armature is within a predetermined distance of a desired location. 30
20. The variable reluctance linear motor of claim 18 further comprising at least one bearing mounted to said armature via at least one vibration damper, said bearing contacting said stator such that vibrations in said stator are transmitted to the at least one bearing and dissipated in said vibration damper. 35
21. A variable reluctance linear motor comprising:  
 a stator; 40  
 an armature mounted proximate said stator, said armature having at least two phases and being movable along the length of the stator; and  
 means for calculating phase currents based on position data for the armature and applying said phase currents to said at least two phases; 45  
 wherein said phase currents are calculated to maintain a minimum normal force between said armature and said stator. 50
22. The variable reluctance linear motor of claim 21 further comprising means for reducing said phase currents when said armature is within a predetermined distance of a desired location. 55
23. The variable reluctance linear motor of claim 21 further comprising  
 means for transmitting vibrations in said stator to said armature; and  
 means for dissipating said vibrations at said armature
24. A method for reducing vibration in a variable reluctance linear motor having an armature, a stator and at least two phases, said method comprising:  
 obtaining position data for the armature with respect to the stator;  
 calculating phase currents for said at least two phases based on said position data; and  
 applying said phase currents to said at least two phases;  
 wherein said phase currents are calculated to maintain a minimum normal force between said armature and said stator.
25. A variable reluctance linear motor comprising:  
 a stator;  
 an armature mounted proximate said stator, said armature having at least two phases and being movable along the length of the stator;  
 a controller for calculating phase currents based on position data of said armature and applying said phase currents to said at least two phases;  
 means for reducing said phase currents when said armature is within a predetermined distance of a desired location.
26. The variable reluctance linear motor of claim 25 wherein said controller calculates said phase currents based on velocity data, and wherein said means for reducing said phase currents comprises means for limiting said velocity data to a predetermined velocity range.
27. The variable reluctance linear motor of claim 26 wherein said controller calculates said phase currents by applying a velocity loop gain to said velocity, and wherein said means for reducing said phase currents comprises means for reducing said velocity loop gain.
28. The variable reluctance liner motor of claim 25 wherein said controller calculates said phase currents by applying a velocity loop gain, and wherein said means for reducing said phase currents comprises means for reducing said velocity loop gain.
29. A variable reluctance linear motor comprising:

a stator;  
an armature mounted proximate said stator,  
said armature having at least two phases and  
being movable along the length of the stator;  
means for calculating a force command based       5  
on position data and velocity data of said arma-  
ture;  
means for reducing said force command when  
said armature is within a predetermined dis-  
tance of a desired location; and                   10  
means for calculating phase currents based on  
said force command and applying said phase  
currents to said at least two phases.

30. A method for reducing vibration in a variable reluc-       15  
tance linear motor having an armature with at least  
two phases and a stator, said method comprising:

obtaining position data for the armature with  
respect to the stator;                                   20  
determining velocity data for the armature;  
calculating a force command based on said  
position data and said velocity data;  
reducing said force command when said arma-       25  
ture is within a predetermined distance of a  
desired location.  
calculating phase currents based on said force  
command, and  
applying said phase currents to said at least  
two phases   30

31. The method of claim 30 wherein the step of reduc-  
ing said force command comprises reducing a  
velocity loop gain.   35

32. The method of claim 30 further comprising limiting  
said velocity data to a predetermined velocity range  
when said armature is within said predetermined  
distance of said desired location.                          40

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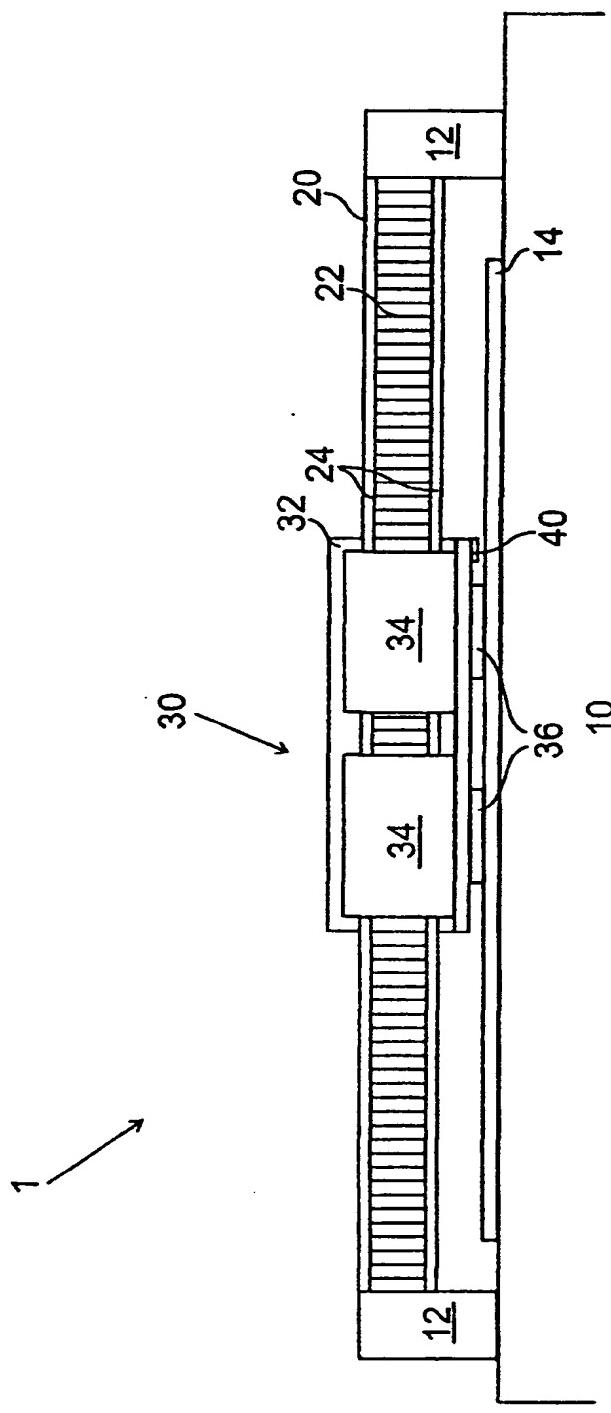
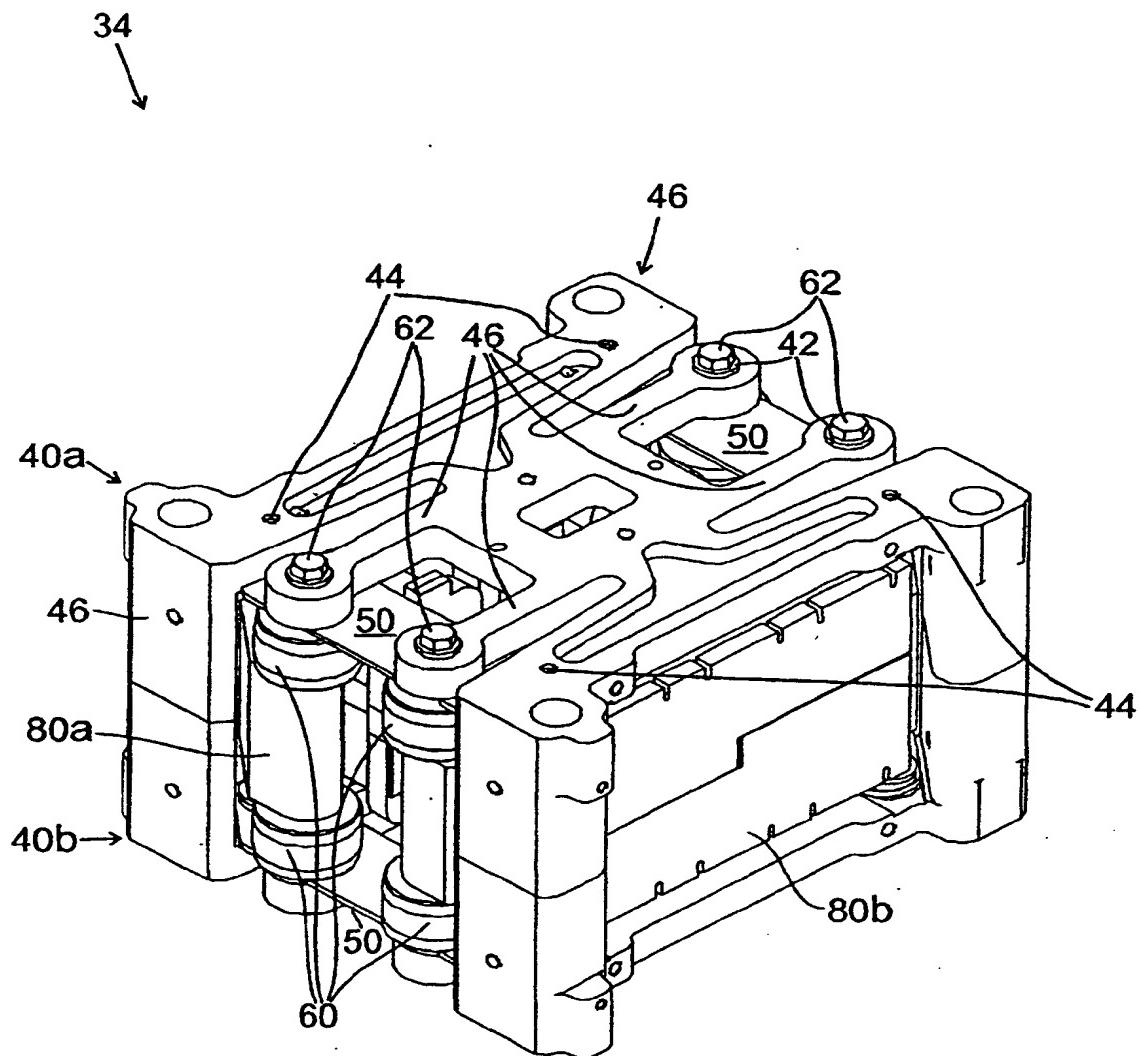
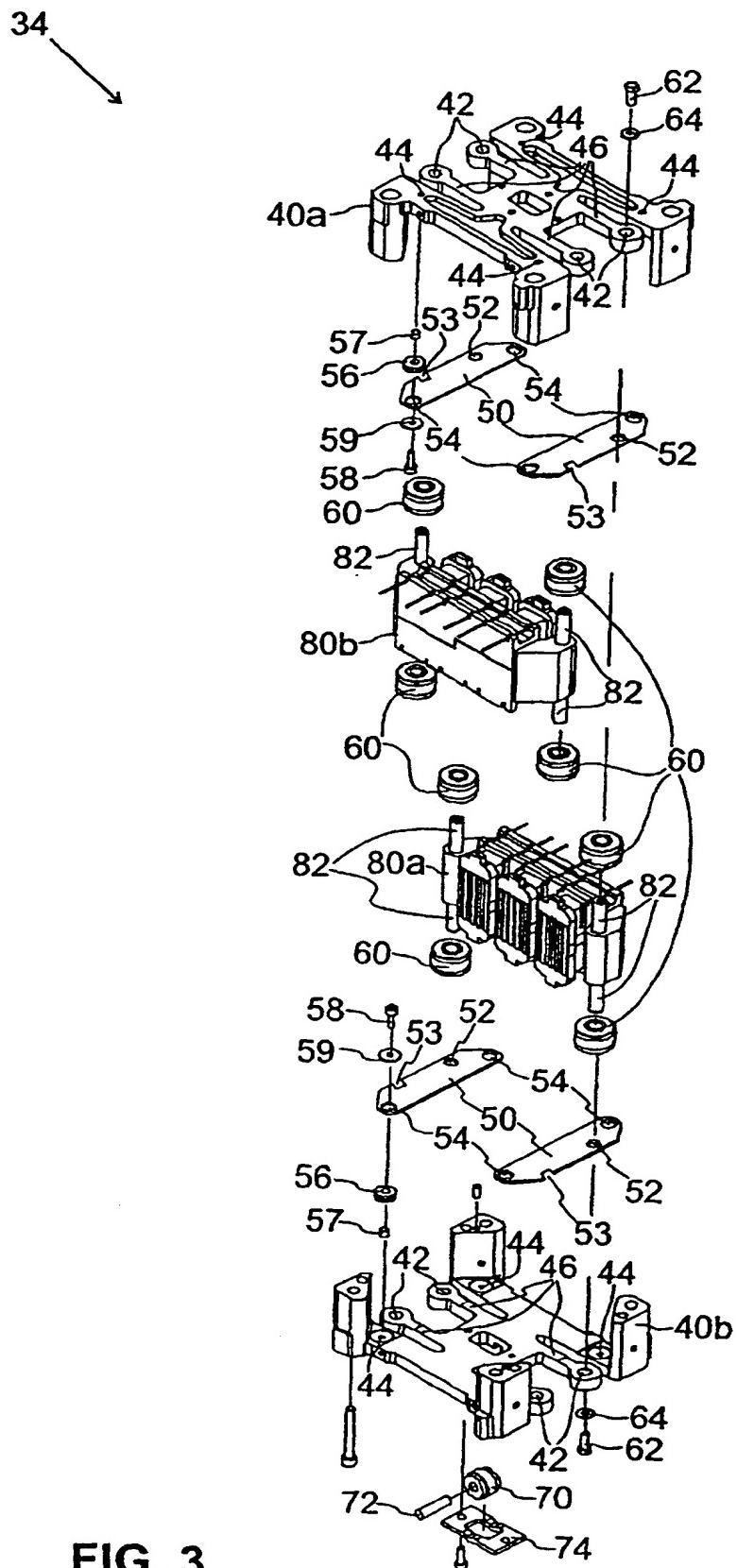
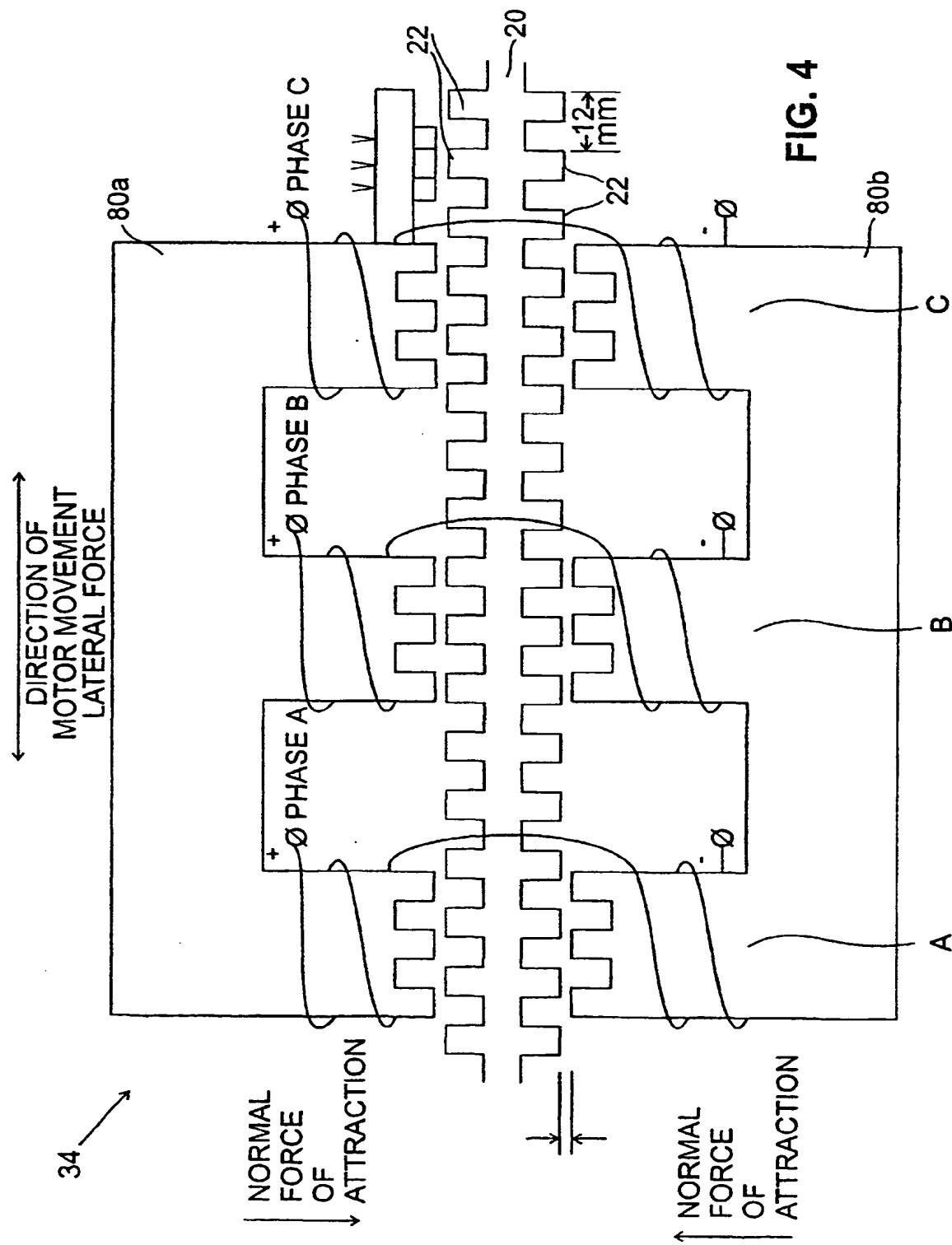


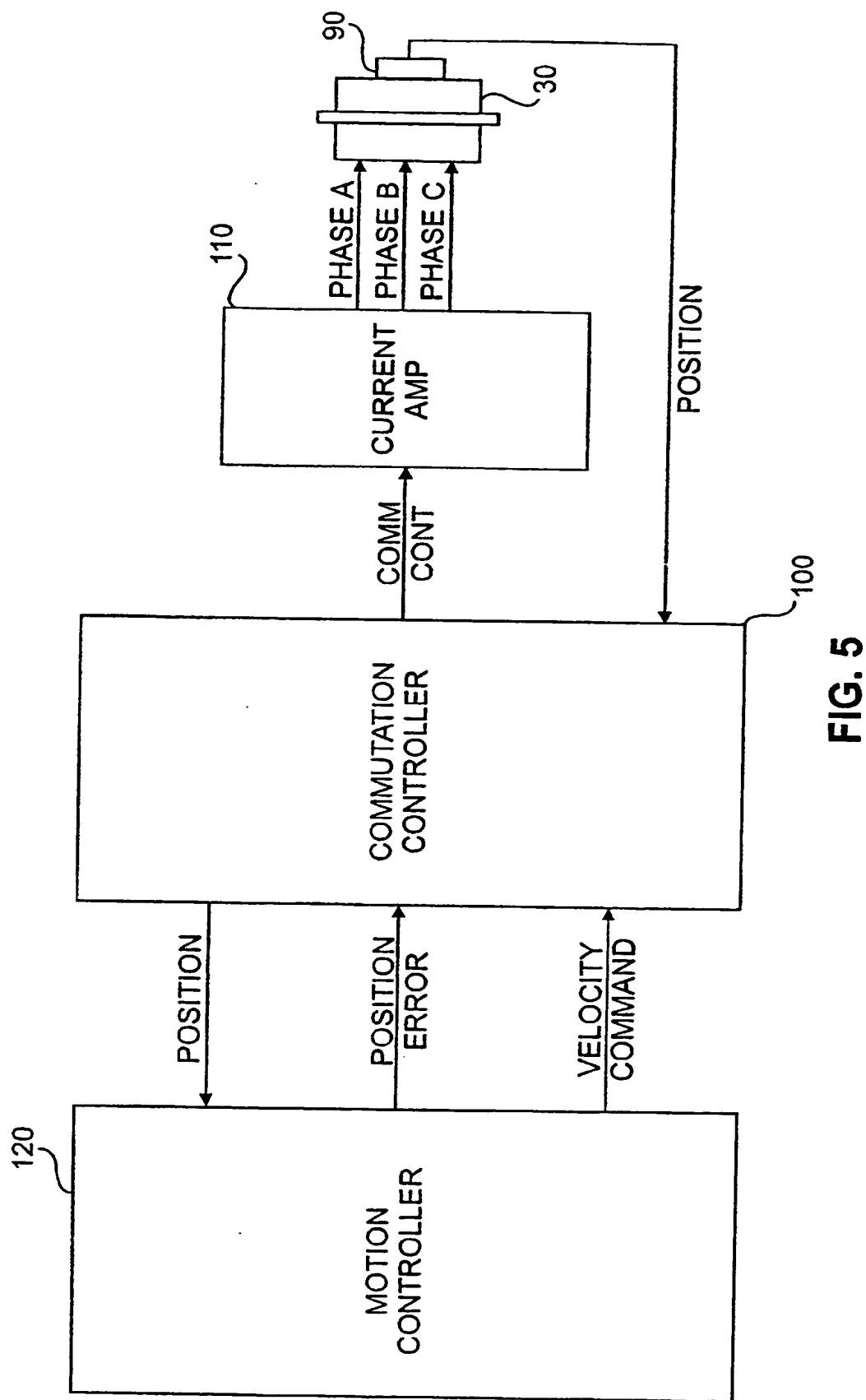
FIG. 1



**FIG. 2**

**FIG. 3**





**FIG. 5**

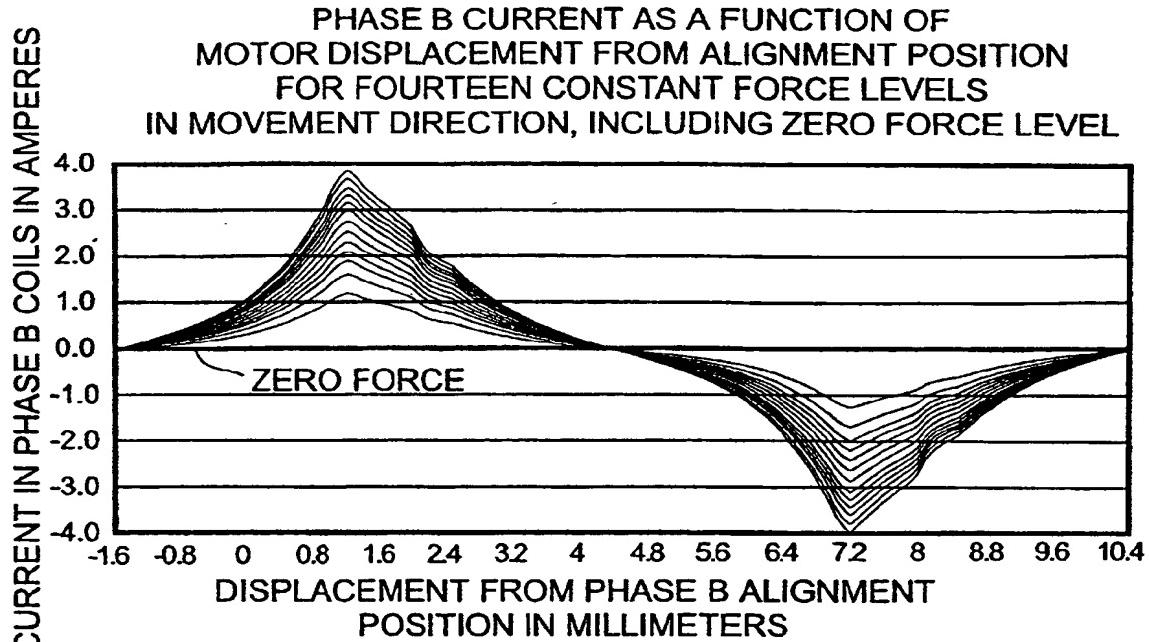


FIG. 6A  
PRIOR ART

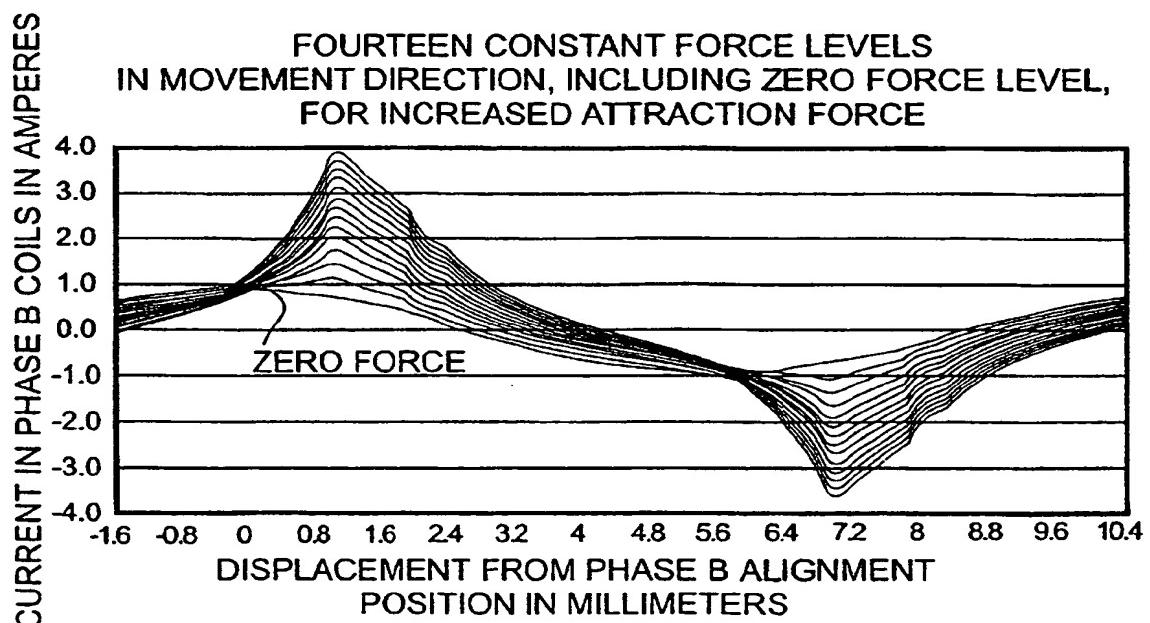


FIG. 6B

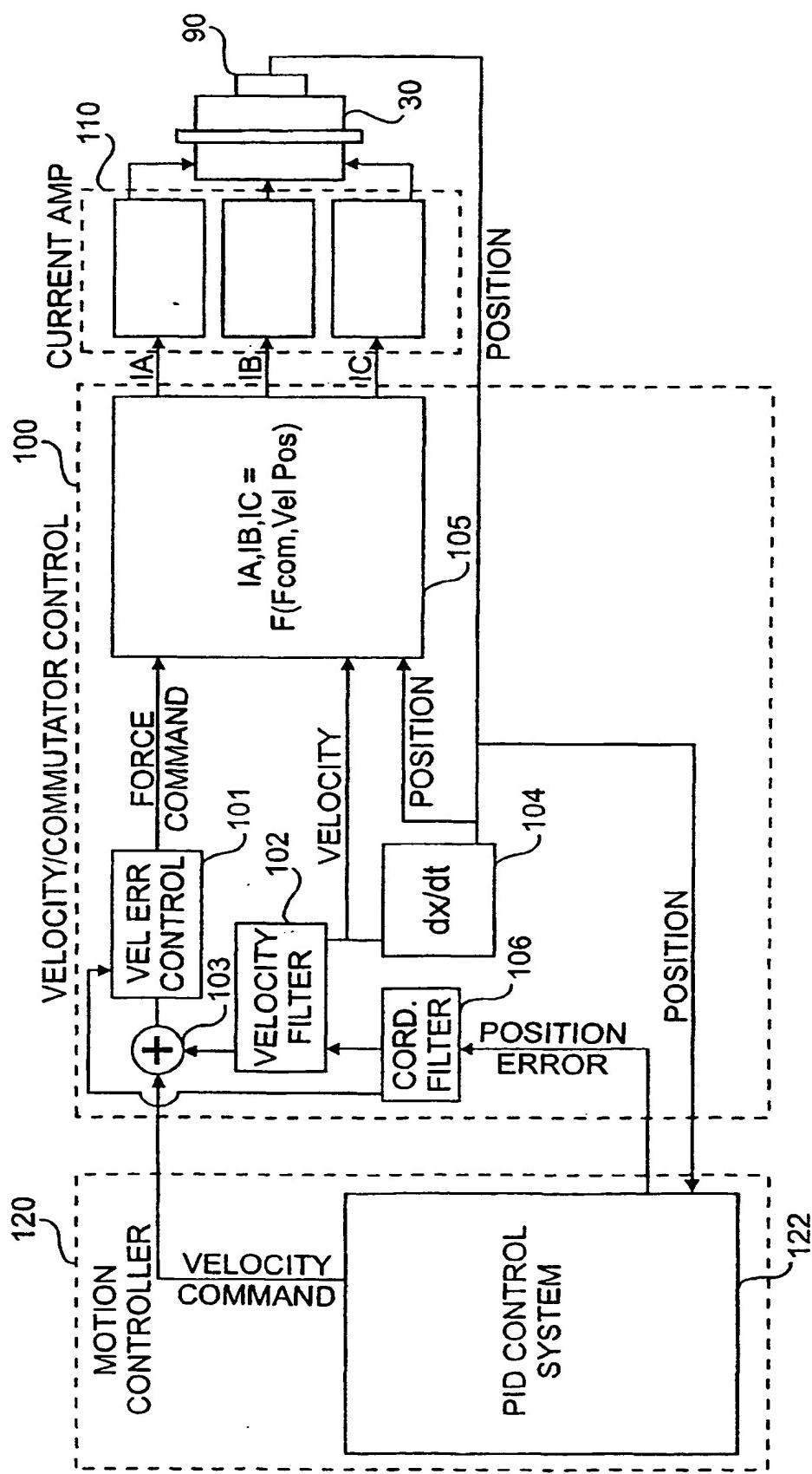


FIG. 7

NO CONDITIONAL FILTER

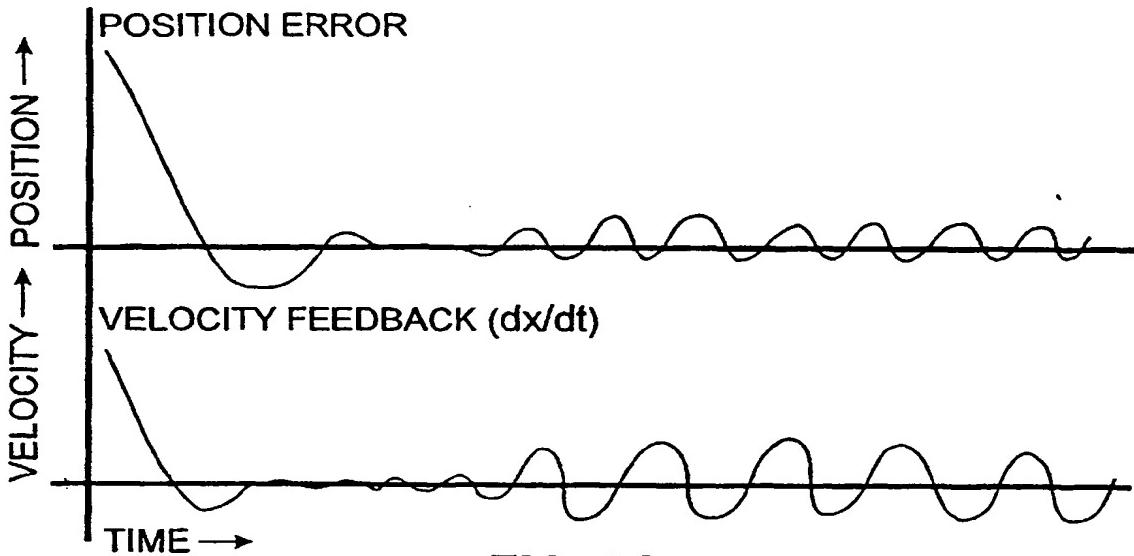


FIG. 8A  
PRIOR ART

WITH CONDITIONAL FILTER

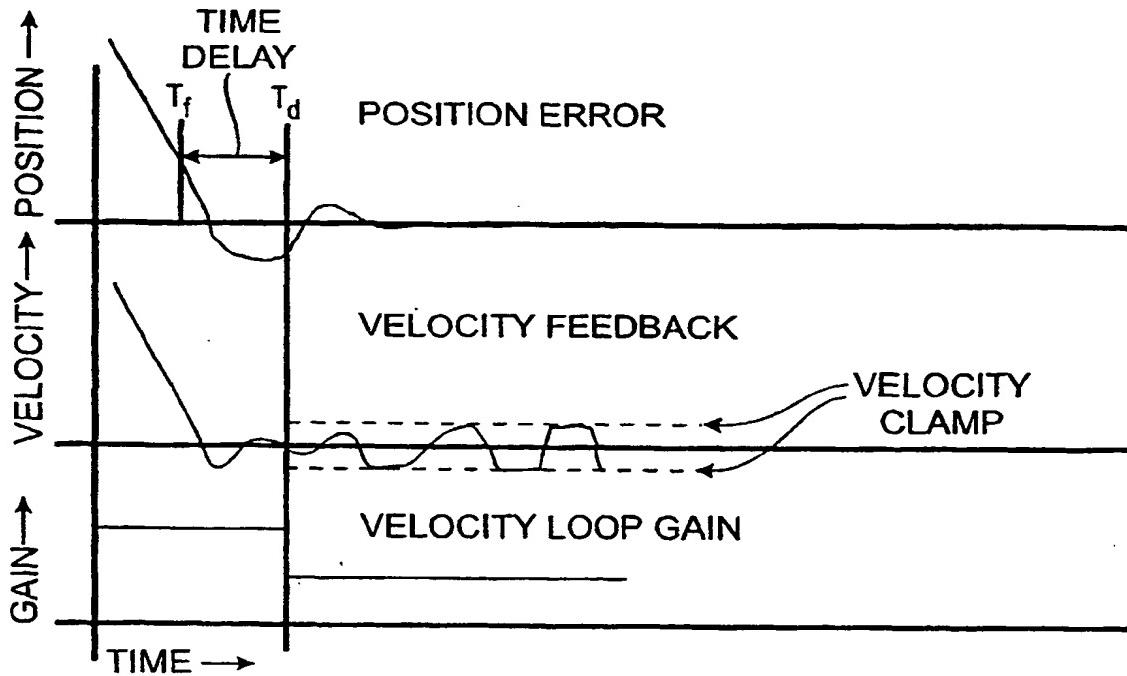
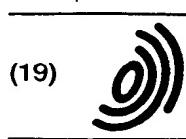


FIG. 8B



(19)

Europäisches Patentamt  
European Patent Office  
Office européen des brevets



(11)

EP 0 961 392 A3

(12)

## EUROPEAN PATENT APPLICATION

(88) Date of publication A3:  
30.08.2000 Bulletin 2000/35

(51) Int. Cl.<sup>7</sup>: H02K 41/03, H02K 5/173,  
H02P 6/00

(43) Date of publication A2:  
01.12.1999 Bulletin 1999/48

(21) Application number: 99302535.2

(22) Date of filing: 31.03.1999

(84) Designated Contracting States:  
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU  
MC NL PT SE

Designated Extension States:  
AL LT LV MK RO SI

(30) Priority: 08.04.1998 US 58004

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**(54) Method and apparatus for vibration reduction/control in a variable reluctance linear motor**

(57) A variable reluctance linear motor has a stator and an armature mounted so as to be movable along the length of the stator. Armature bearings are mounted to the armature via mechanical vibration dampers and contact the stator so that vibrations in the stator are transmitted to the bearings and dissipated in said vibration dampers. A sensor is mounted to the armature for obtaining position data for the armature with respect to the stator. A controller then calculates the phase currents for the motor phases based on the position data and a desired force value. The phase currents are calculated to maintain a minimum normal force between the armature and said stator, thereby further reducing vibrations. A conditional filter is applied when armature is within a predetermined distance from a desired location. The conditional filter, after a time delay, clamps the velocity feedback to a predetermined range and simultaneously reduces the velocity loop gain.

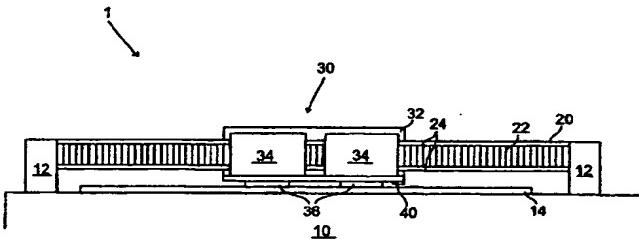


FIG. 1



European Patent  
Office

## EUROPEAN SEARCH REPORT

Application Number  
EP 99 30 2535

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)						
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A	PATENT ABSTRACTS OF JAPAN vol. 012, no. 003 (E-570), 7 January 1988 (1988-01-07) & JP 62 163557 A (SHINKO ELECTRIC CO LTD), 20 July 1987 (1987-07-20) * abstract * -----								
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)						
			H02K H02P						
<p>The present search report has been drawn up for all claims</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%;">Place of search</td> <td style="width: 33%;">Date of completion of the search</td> <td style="width: 33%;">Examiner</td> </tr> <tr> <td>THE HAGUE</td> <td>6 July 2000</td> <td>Ramos, H</td> </tr> </table> <p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone  Y : particularly relevant if combined with another document of the same category  A : technological background  O : non-written disclosure  P : intermediate document</p> <p>T : theory or principle underlying the invention  E : earlier patent document, but published on, or after the filing date  D : document cited in the application  L : document cited for other reasons  &amp; : member of the same patent family, corresponding document</p>				Place of search	Date of completion of the search	Examiner	THE HAGUE	6 July 2000	Ramos, H
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THE HAGUE	6 July 2000	Ramos, H							

**ANNEX TO THE EUROPEAN SEARCH REPORT  
ON EUROPEAN PATENT APPLICATION NO.**

EP 99 30 2535

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